

The Support and Alignment of the Stanford Linear Accelerator (A)  
Introduction

In April, 1962, the Atomic Energy Commission awarded Stanford University a contract to design and construct at an expected cost of \$114,000,000 a two mile long linear electron accelerator. The accelerator was completed in November, 1966, more than twenty years after Stanford scientists began research on linear accelerators. It produces an electron beam of 10 to 20 billion electron volts and is available to scientists from all nations for research in the fields of particle and high energy physics. A 300 foot linear accelerator (the Mark III) capable of producing I Bev electrons was built at Stanford in 1951 and was for a number of years the largest linear accelerator in the country. The Stanford machines, which accelerate electrons along a straight line, have some advantages over machines which accelerate in a circular path. This is due to the fact that high energy electrons traveling in a circular path lose large amounts of energy through radiation. Not only does the lost energy never reach the target, but also it creates a radiation hazard to personnel.

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Prepared in the Design Division of Mechanical Engineering Department by  
Sue Hays under the direction of Professor Henry O. Fuchs with support from  
the National Science Foundation.

The accelerator, which costs \$20,000,000 per year to operate, is essentially a copper pipe 4 inches in diameter and two miles long. An electron beam is produced by injecting electron bunches into one end of the pipe 360 times per second. At the other end of the pipe is a "beam switchyard". Here, the electron beam is steered by magnets into one of several experimental areas, where the beam hits its target. This switchyard arrangement permits scientists to set up an experiment while another is being run.

The pipe itself is housed in a concrete tunnel buried under 25 feet of earth to provide shielding from the radiation produced when the accelerator is running. On the surface, 25 feet above the tunnel and parallel to it, is a gallery which houses the klystrons which produce the microwave power used to run the accelerator.

The accelerator pipe was assembled from over 80,000 copper discs and cylinders interspaced with brazing washers made from a copper-silver alloy. Stacks of 80 discs, cylinders, and washers were brazed into solid units 10 feet long. Approximately 1000 such units were made. Small copper tubes for carrying cooling water were brazed to the exterior of each of the 1000 foot units (see Exhibits 1 and 2 for photographs). Each 10 foot section is mounted on a "strongback", with intermediate supports to prevent sagging of the heavy soft copper pipe.

The 10 foot accelerator pipe sections were placed in groups of four atop 40 foot long aluminum pipes two feet in diameter. The primary function of the larger pipes (called "support girders") is to provide strength and rigidity for the accelerator pipe. 240 of the 40 foot support girder accelerator pipe assemblies were connected together and aligned to form the two mile structure (see Exhibits 3 and 4).

Radio frequency power to each 40 foot section is supplied by a single high power klystron amplifier tube. Every 10 feet, a waveguide feeds one fourth the power produced by the klystron into the accelerator pipe.

### The Overall Alignment Problem

One major question which the designers of SLAC had to resolve was how straight to make the accelerator pipe. The pipe must be straight enough so that not too many electrons collide with the pipe. The electrons which do collide with the pipe produce undesirable radiation. Also, as many electrons as possible should hit the target. Steering magnets can refocus and guide electron beams. However, it is less expensive to build a relatively straight accelerator pipe and to use only a moderate number of steering magnets than it is to steer a beam down a less straight pipe with a large number of magnets. After considering this problem at some length, the physicists at SLAC decided that the accelerator pipe should be within 1/8 inch of straightness over its two mile length. In other words, the center of the cross-section of the pipe at any place along its length should not be more than 1/8 inch from some straight reference line.

As a matter of interest, the reader may consider that, due to the earth's curvature, the ends of a two mile level straight line would be about 16 inches farther from the center of the earth than the middle of the line would be. In addition, the accelerator is straight but not level; one end is about 50 feet lower than the other.

### Complicating Factors

During the design and construction of the accelerator, SLAC engineers had to contend with a number of factors which made the 1/8 inch of straightness requirement a hard one to meet.

Differences in temperature and in thermal expansion were among these factors. When the accelerator is in operation, the copper accelerator pipe itself is about 115° F, while its aluminum supporting structure remains somewhat cooler. Also, parts made in the shop at one temperature change size when installed in the gallery at another temperature. The differences in thermal expansions of the materials should not buckle or distort the structure.

Another problem the engineers knew they would have was that the accelerator pipe would tend to sag under its own weight. The pipe is made of very pure copper (for its electrical conductivity), which is quite soft.

Earthquakes sometimes occur in the vicinity (near San Francisco) of the accelerator location. The structure is not required to remain within alignment tolerance during an earthquake but is supposed to return to its original alignment after an earthquake. Engineers designed the structure so that its natural frequency is outside the predominant earthquake frequency range of 1 to 10 cycles per second.

The engineers anticipated that small corrections in the alignment might have to be made from time to time. Because the expense of supporting and aligning one 40 foot section would be multiplied 240 times, the engineers wanted to find an efficient design for the support and alignment system.

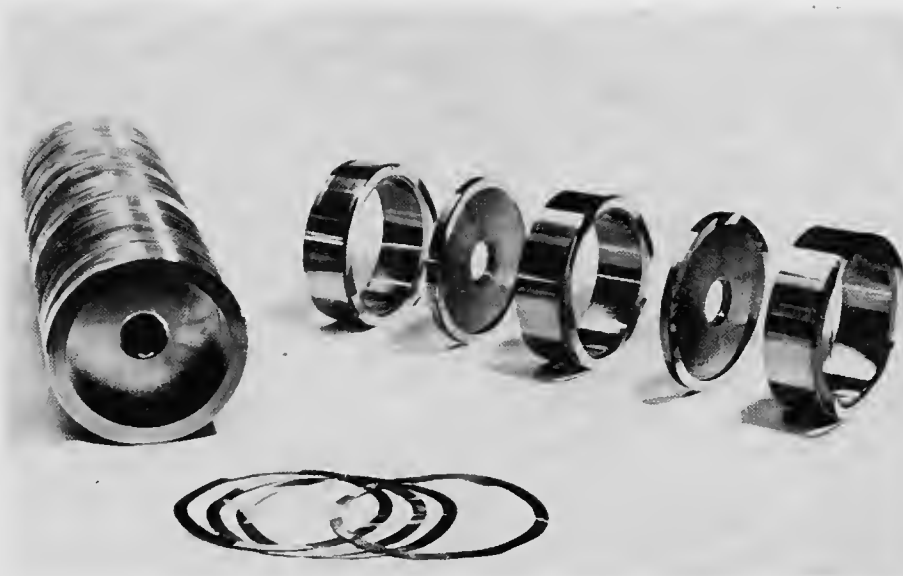


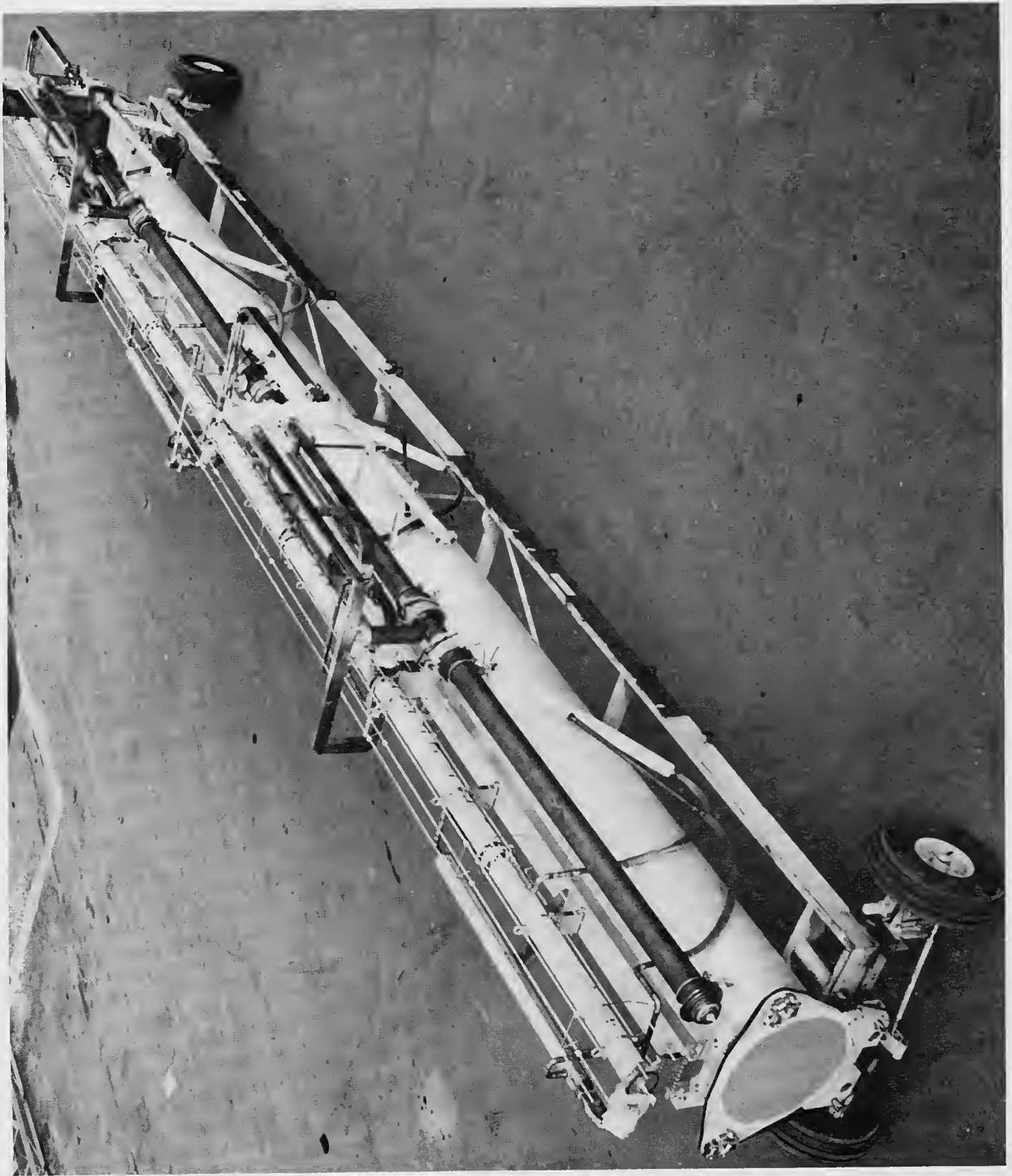
Exhibit 1

These copper discs and cylinders make up the 4 inch diameter accelerator pipe. One of the thin alloy rings in the foreground is placed between each pair of copper parts for brazing the pieces together.

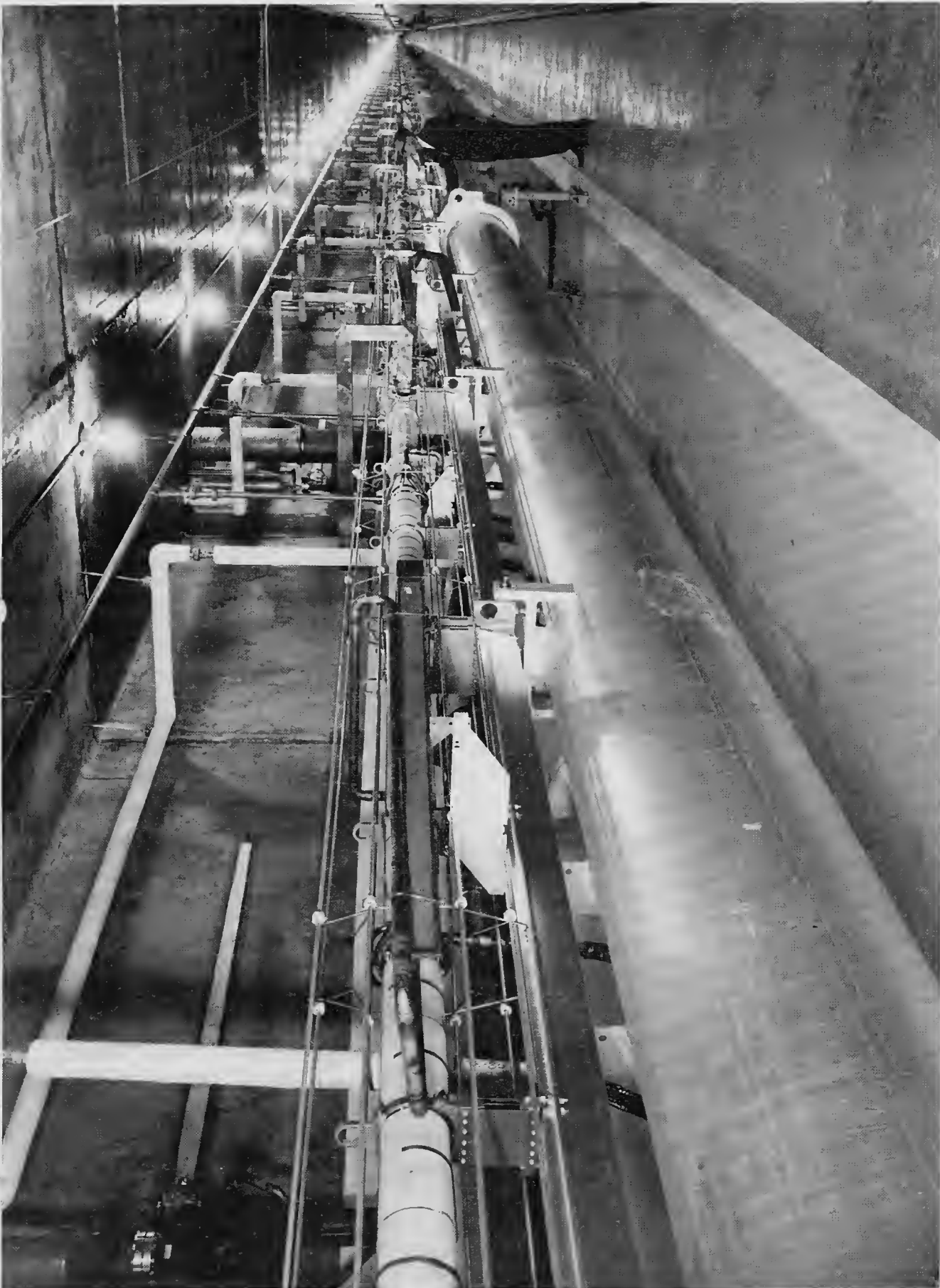


Exhibit 2

Assembled 10 foot section of accelerator pipe, shown mounted to an aluminum "strong back" for support. The entire assembly is later mounted to the support girder.



Section of accelerator pipe mounted on support girder.



Two mile long linear accelerator completely assembled.

## The Support and Alignment of the Stanford Linear Accelerator (B)

### The Girder Interconnection and Support

The mechanical engineers at SLAC were asked to design an interconnection and support scheme for the 240 forty foot assemblies which make up the linear accelerator. Because the girder interconnections would be a crucial part of the overall alignment of the accelerator, virtually all of the technical personnel, including the physicists and SLAC's director Dr. Panofsky, thought about the interconnection problem. Everyone was concerned that some important detail might be overlooked. There were no precedents for the design of an accelerator the size of SLAC. No one knew how stringent to make the requirements or how hard it would be to meet the requirements they imposed. The technical groups discussed the interconnection problem with each other for a few weeks and came up with the following guide lines:

1. It had to be possible to adjust the ends of the girders up and down and from side to side so that the center lines of the girders could be brought into a single straight line. Geometrically, this meant that the joints had to permit adjustment of the angles between adjacent center lines to zero. The joints also had to allow the adjustment of the end points of adjacent center lines so that the endpoints could be made to coincide.

2. Because the engineers would not be able to check the alignment of the accelerator pipe itself, the alignment of the girders had to guarantee the alignment of the accelerator pipe. In each 40 foot section, the accelerator pipe was assembled parallel to the girder center line and at a precise distance from it. The accelerator pipes would be made parallel by aligning the

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girder center lines. Then the girders would be rotated about their center lines until the accelerator pipe sections would be not only parallel, but also colinear. Thus, the joints had to constrain rotation of the girders about their center lines except for adjustment. (See Figure 1).

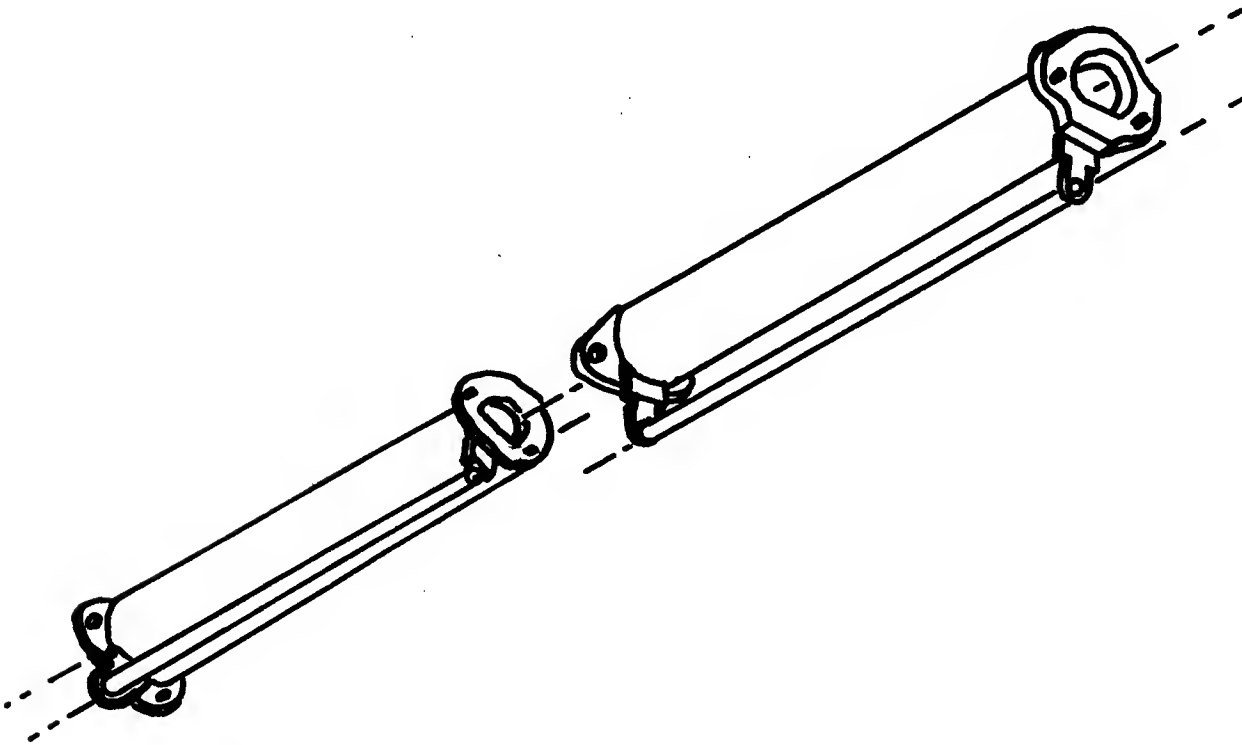


Figure 1. Accelerator pipe misalignment resulting from rotation of support girders with respect to one another.

3. Thermal expansion and contraction of the girders had to be accommodated.
4. The joints had to be vacuum tight, as both the accelerator pipe and the two mile length of support girders were to be evacuated.

The basic plan for the interconnection was to support the upstream end of each 40 foot section with jacks and to support the downstream end by mating it with the jack-supported end of the adjacent section.

Flexible bellows between girders and between accelerator sections would provide the required closed systems. (See Figure 2).

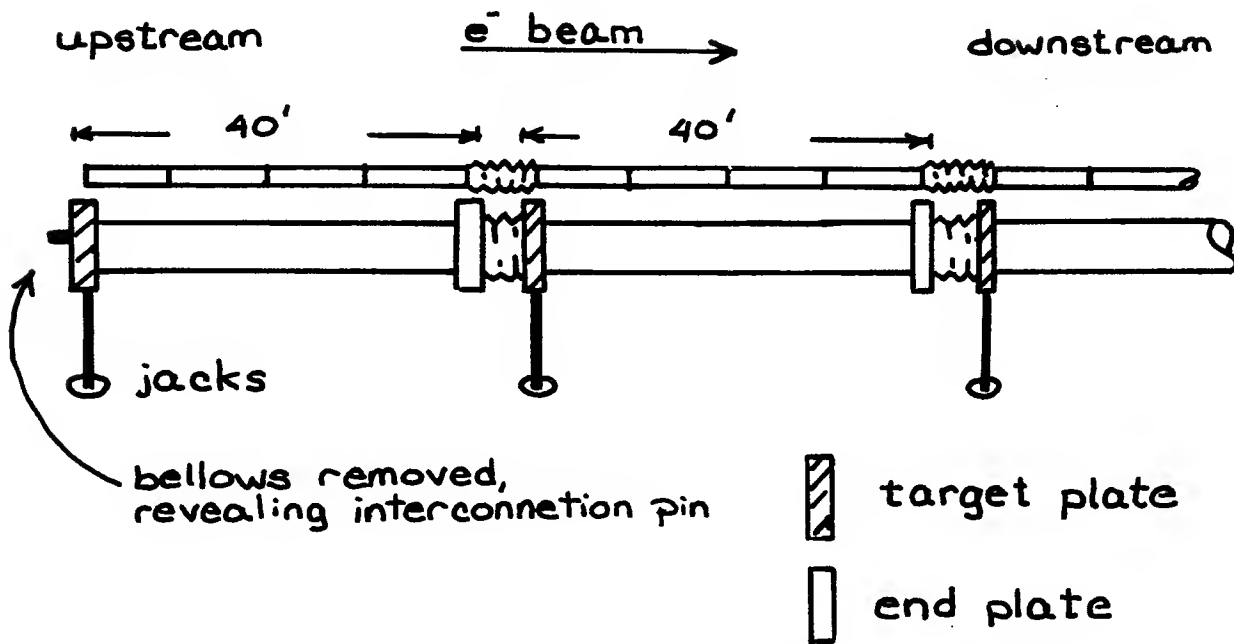
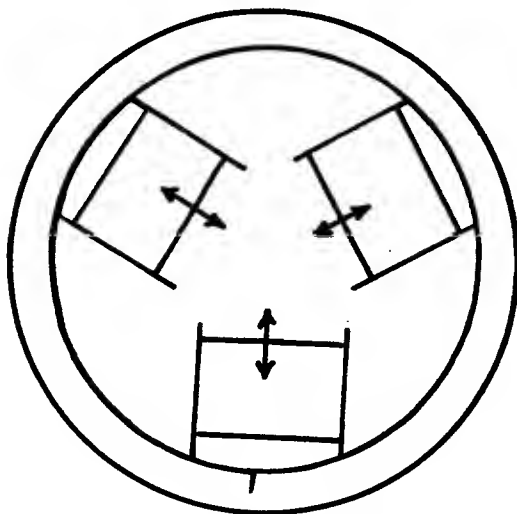


Figure 2. Girder support and interconnection scheme

A 1-1/2 inch thick aluminum "end plate" (Exhibit 3) is welded to the downstream end of each 40 foot section. Two socket assemblies are mounted to each end plate. One of the socket assemblies consists of two roller bearings and the other (Exhibit 1), of three roller bearings. The positions of the bearings in the sockets are adjustable. (See Figure 3).



rollers adjustable in these directions

Figure 3. Direction of roller bearing adjustment

The upstream end of each 40 foot section is welded to a target plate or target housing (Exhibit 2). A target for the laser beam to be used in aligning the accelerator is mounted to each target plate - hence its name. Two hexagonal steel pins (Exhibits 4 and 5) are also mounted in this plate.

Two hexagonal pins to be mounted in the target plate of one section mate with the roller bearing assemblies mounted on the end plate of the adjacent section to provide the intergirder connection. The pin and bearing assembly connection permits small angular changes and lengthwise changes of about 1/2 inch (see Exhibit 7 for photographs). Should the girders expand, the pins would roll farther into the bearing assemblies. The pin which fits into the two-roller bearing assembly is able to move axially and can also accomodate manufacturing tolerance to build-up in the horizontal direction. The pin fitting through the three-roller assembly permits axial motion only. This configuration prevents over-constraint of the pins. The pin and bearing assemblies also prevent relative rotation of adjacent girders. The fact that the roller bearings are adjustable as shown in Figure 3 permits small adjustments in the position of the downstream end of one section relative to the upstream end of the adjacent section during initial alignment operations. Adjustable jacks are used to bring the chain of girders into alignment.

Three adjustable worm screw jacks support the upstream end of each girder. Two of the jacks are bolted to the floor and one to the wall. (see Figure 4). Ball joints connect the jacks to the target plate. The engineers decided to spring load the floor jacks in such a way that small differences in jack height on the right and left side produce only a very small twisting torque on the support girder. This scheme prevents the adjustment of the jacks from twisting the girders relative to each other.

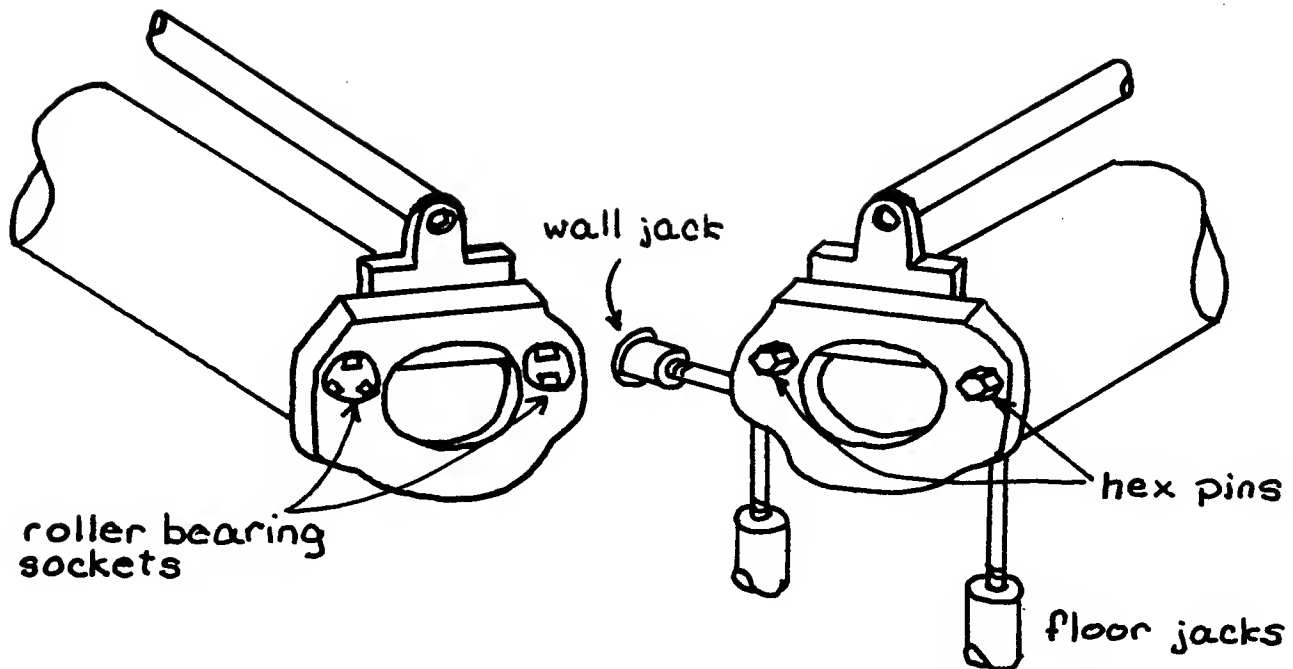


Figure 4. Ends of two adjacent girders showing interconnection pins and rollers

Kaiser Aluminum Company and Kaiser Steel Fabricators provided the  $\frac{3}{8}$  inch ( $\pm .010$ ) thick aluminum support girders, which have an outside diameter of 24 inches ( $+ \frac{1}{32}$ ,  $- \frac{3}{32}$ ). FMC Corporation welded the target plates, end plates and other parts to the girders. The inside diameter of the end plates was made slightly larger than the outside diameter of the support girder pipes so that the plates could be slipped over the girders and adjusted until the assembly had the correct length ( $\pm \frac{1}{16}$ "). The Precision Grinding Company supplied the pins and roller-bearing assemblies.

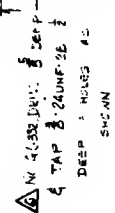
A number of problems arose in the production and assembly of the interconnection parts. Dr. Panofsky pointed out that any slight misalignment of the girders would produce edge bearing in the hexagonal pin and roller-bearing connections. Tests had showed that 2 inch diameter round pins would fail - a consequence of their insufficient contact area. Therefore, the hexagonal pins were crowned with a 53 inch radius on each face contacting the roller-bearings. These showed no measurable wear during tests. The radii of the faces were made as large as would be practical while still permitting easy observation of the contact point of the rollers on the pin surfaces.

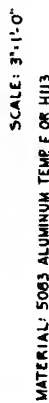
Alignment between adjacent sections was checked by sighting through the optical tooling holes in one section to targets placed in the tooling holes of the adjacent section. Manufacturing tolerances of the interconnection parts roughly aligned the sections. The final, fine adjustments in alignment were made by adjusting the roller bearings. Much thought was devoted to the design and tolerancing of the end plates and target plates. The drawings show that eight changes were made between January and June, 1964. Mr. Sandkuhle, who designed the plates, says that due to recent changes in dimensioning practices and to hindsights he gained from doing his job, he would dimension the plates differently now. Exhibit 6 shows how Mr. Sandkuhle would now dimension the target plate.

#### Exhibits

- |           |  |
|-----------|--|
| Exhibit 1 | Support & Alignment, 3 Roller Bearing Plate Assembly, Inter Girder Connection, AD 861-452 R0 |
| Exhibit 2 | Support Girder, Girder Assembly Target Housing, PF 861-106-01 R8                             |
| Exhibit 3 | Support Girder, Girder Assembly End Plate, PF 861-106-02 R6                                  |
| Exhibit 4 | Support & Alignment, 2 Roller Pin, Inter Girder Connection, PF 861-452-02 R1                 |
| Exhibit 5 | Support & Alignment, 3 Roller Pin, Inter Girder Connection, PF 861-452-03 R1                 |
| Exhibit 6 | Proposed Revisions to Drawing PF 861-106-01  |
| Exhibit 7 | Interconnection Photographs  |







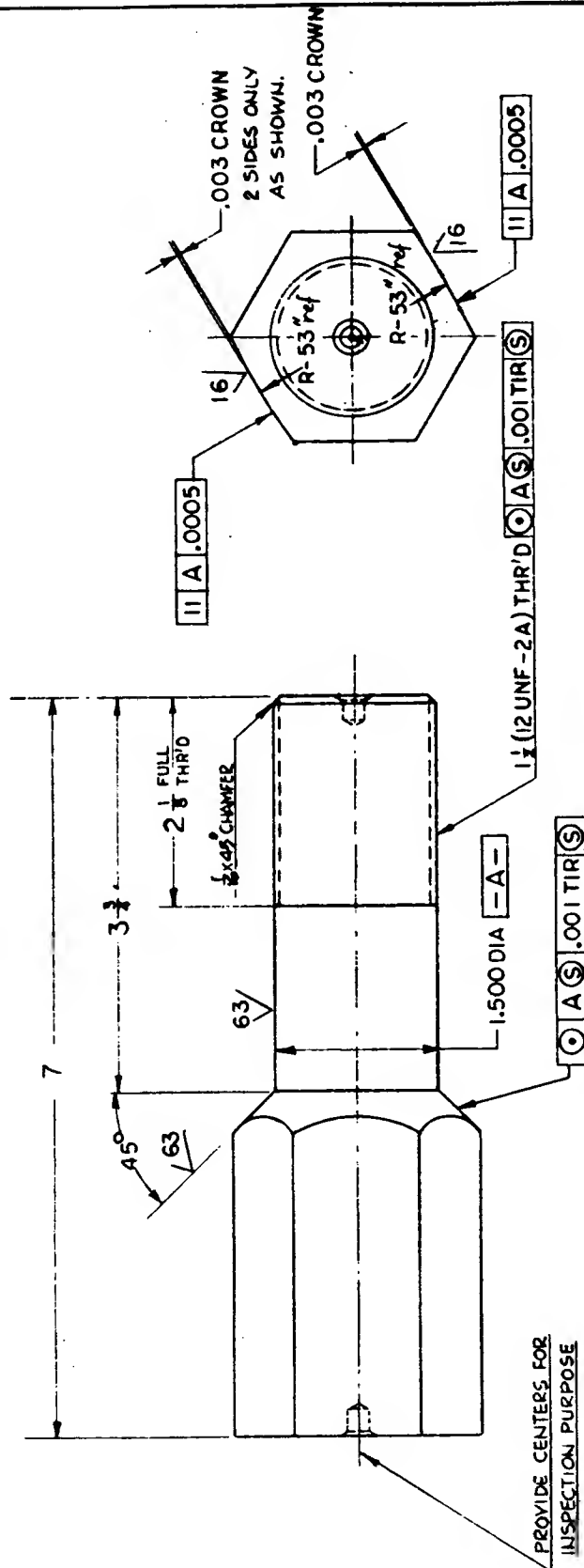
UNLESS NOTED  
TOLERANCES BREAK CORNER .003  
FACT.  $\pm .04$  INT. RAD. .015  
DEC.  $\pm .005$  GRO  
ANGLES  $\pm 1/2^\circ$

**A-A**  
SCALE: 3" = 1'-0"

(DO NOT SCALE DRAWING)

[illegible]





MATERIAL : STAINLESS STEEL AISI 416, ANNEALED & COLD DRAWN  
 MACHINE FROM 2" HEX BAR.  
 HEAT TREAT TO MIN. ROCKWELL 'C' 40, AFTER MACHINING.  
 GRIND CROWNS AFTER HEAT TREATMENT.

DO NOT SCALE

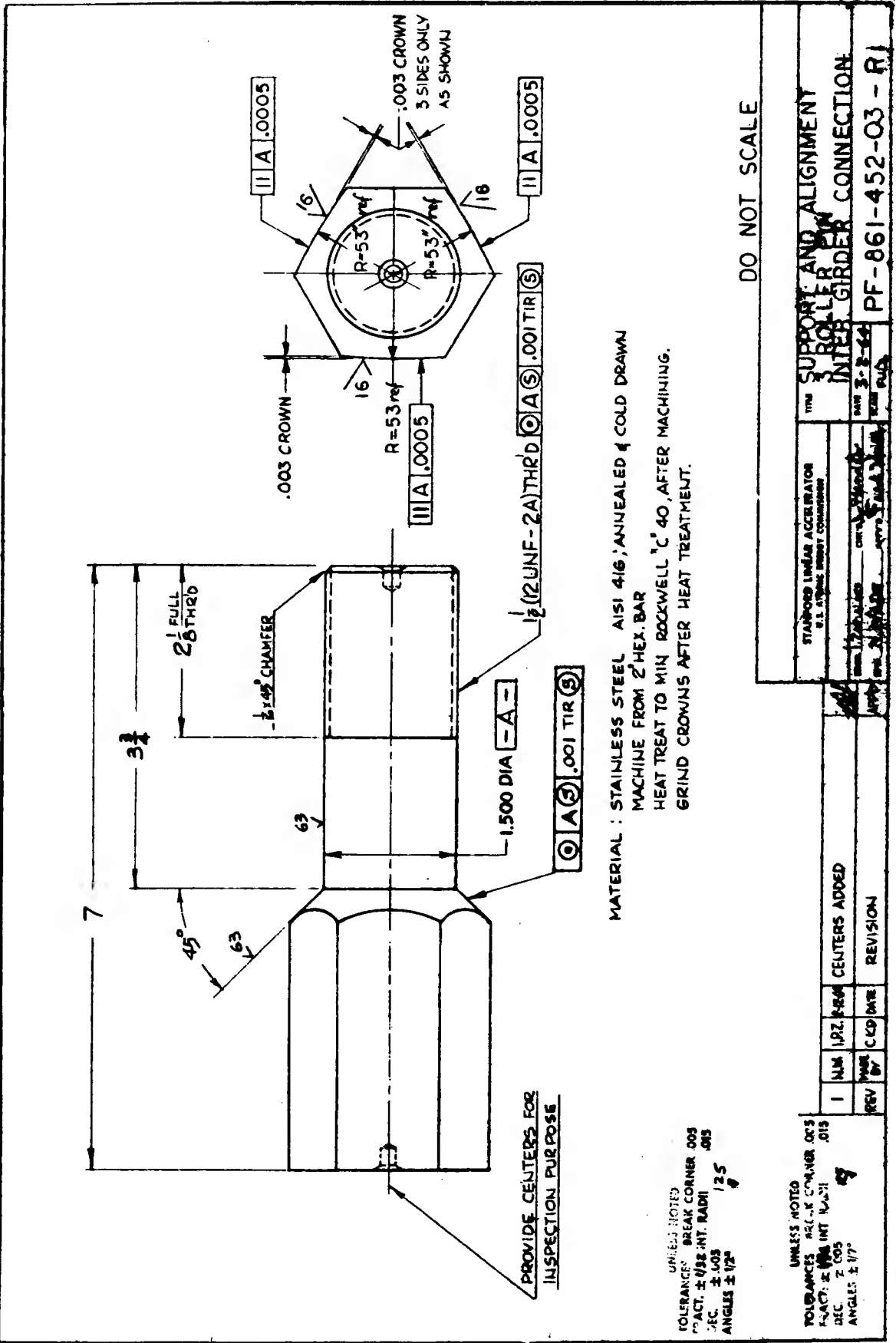
UNLESS NOTED  
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 DEC. ± .005  
 ANGLES ± 1/2°

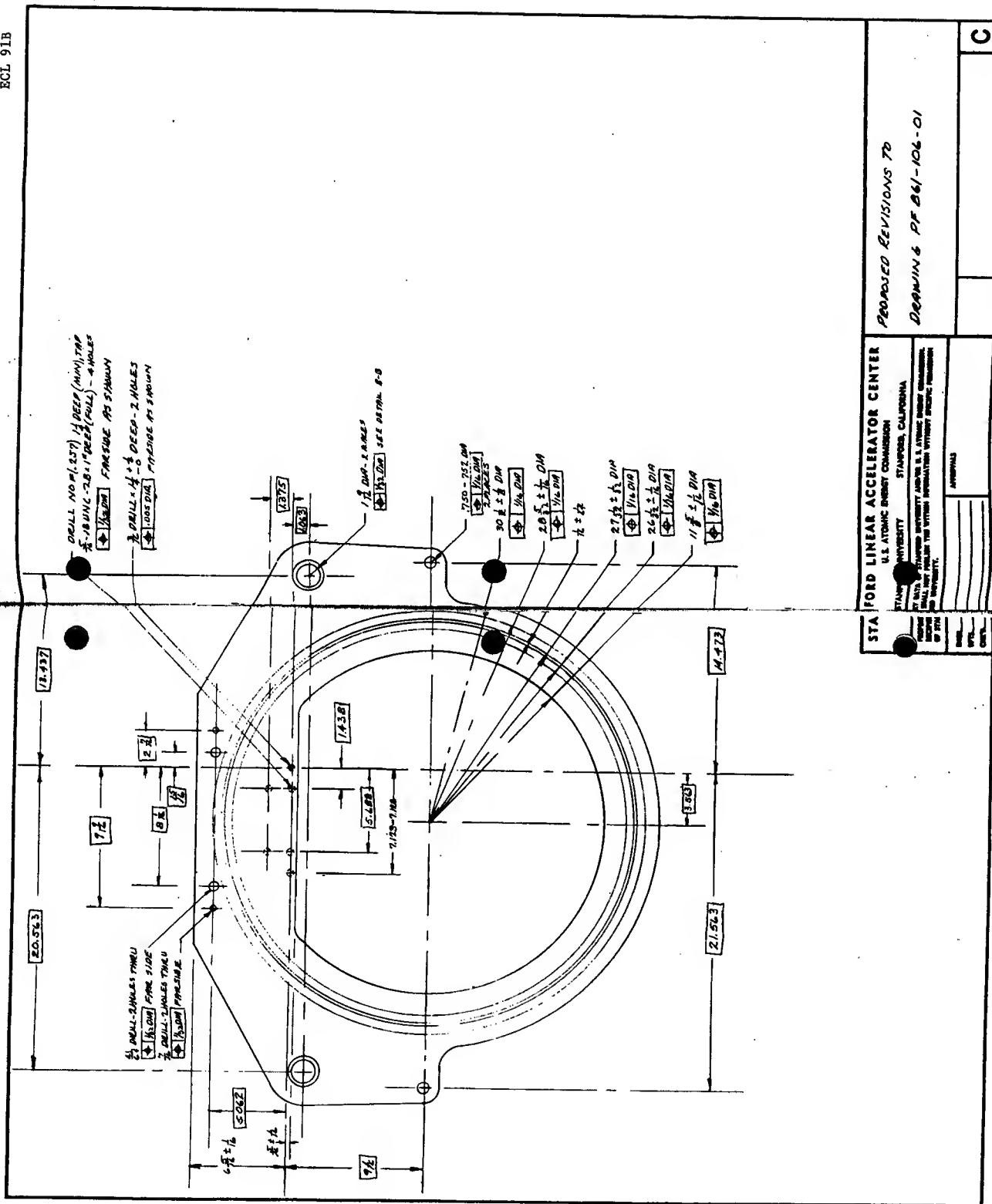
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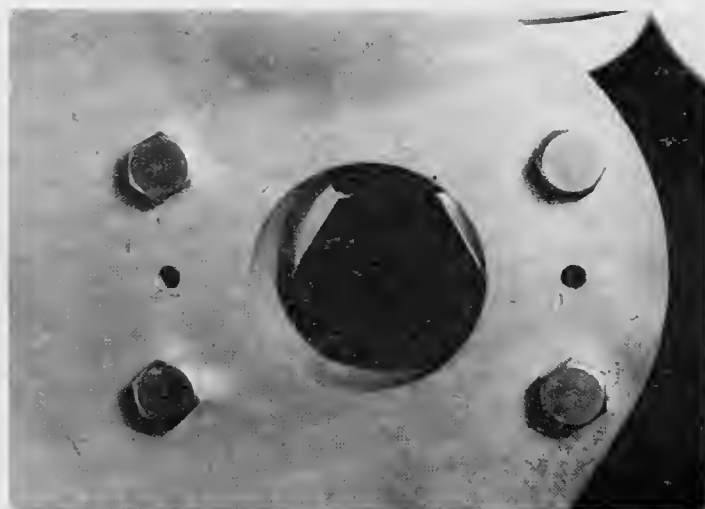
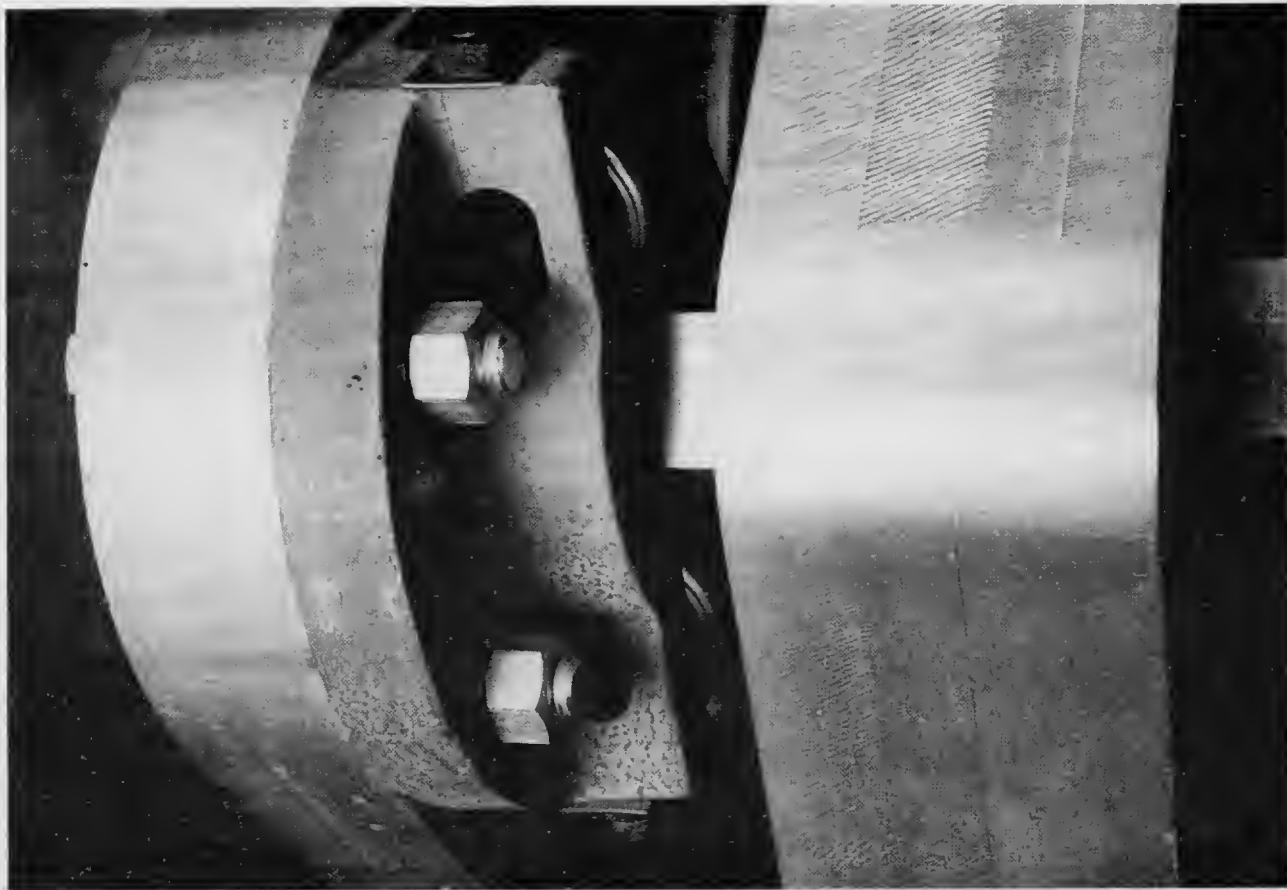
REV	BY	DATE	REVISION
1	NHK	10-2-66	CENTERS ADDED

THE SUPPORT AND ALIGNMENT  
 2" ROLLER PIN  
 INTER GIRDER CONNECTION  
 DATE 10-2-66  
 DRAWN BY N.WABE  
 CHECKED BY J. J. JAMES  
 FULL

PF-861-451-02-R1







## Instructor's Notes

Engineers at SLAC solved the problem of making a tube two miles long straight within 1/8 inch, with the additional difficulty that the inside of the tube is not accessible for checking after the tube has been installed. This is outlined in part A. Part B focuses mainly on some of the important hardware details.

The case may be used for exercises in design, in tolerancing, in error analysis, in strength of materials, and in other ways.

The interconnection of the girders is an excellent design problem. It can either be handled "de novo" by giving students only part A of the case, or as an "iteration" after they have seen part B and are able to use hindsight.

The interconnection could have been achieved in many other ways, and some of these ways have advantages over the solution presented in the case. Among the possible alternatives to the pair of hex pins with crowned sides one might mention:

- Self-aligning bearing pads
- Self-aligning bearing on one side, pads on the other
- Linkages between girders, analogous to the linkage shown in the case between girder and floor
- Flexures, analogous to the flexures shown in the case between the tube and the strong back
- Crowned rollers on flat hex pins.

One can give students practice in creativity by asking them to suggest many feasible ways of interconnecting the girders, practice in critical analysis by asking them to compare the various possible solutions, and practice in other skills by asking them to design one of the alternate solutions in some detail.

The use of the two types of hex pins, which can easily be used in the wrong position, raises interesting questions: Should all the hex pins be the same? Should the two different types be more easily recognized? Should they have different shank diameters to prevent reversed installation?

In tolerancing the case is an excellent example of the division of effort between accurate manufacture and final adjustments. The target housing (Exhibit 3 of part B) has tolerances varying from (+ 1/4 - 0) on the depth of a 3/16 hole to ( $\pm$  0.001) on the diameter of a 3/4 hole. One should ask why. For many of the tolerances it is interesting to ask how they can be verified. The tolerance (0.005 TIR) on the countersinks of the 1-9/16 holes seems especially noteworthy. Mr. Sandkuhle's proposed revisions (Exhibit 6 of part B) bring up the advantages of geometric position tolerancing. Similar questions can be raised about the hex pins.

Error analysis is closely connected with tolerancing. How much error in the accelerator tube can be produced by misalignment of the hex pins when the girders expand or contract?

In strength of materials the case is full of interesting questions: Deflection of the girders under the weight of the structure? (Estimation of the weight is a good exercise in making reasonable approximations). Deflection of the copper tube if intermediate supports are added or omitted? Hertz stresses at the contacts of crowned pins and rollers? Twisting deflections produced by torques from differences in the jack screws? (Deflection of the hex pins will be a major part of this twisting deflection.) Optimum wall thickness of the girders?

Choice of materials can also be discussed. (Magnetic materials must be avoided in the structure.)

Decision: The students may be asked to list a number of decisions which were made by the physicists and engineers, and to divide them into classes by importance (Very important, medium important, unimportant). This will bring out the questions of expressed and implied decision criteria, and also the question of evaluating the importance of a decision.

Many other uses of this case will occur to imaginative teachers.

Interesting background for this case is contained in SLAC report No. 62 "The Story of Stanford's Two-Mile Long Accelerator" by D. W. Dupen. (\$4.00) That report includes a bibliography of 46 publications regarding the accelerator and its construction.